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An infrared imaging search for low-mass companions to members of the young nearby β Pic and Tucana/Horologium associations ⋆

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Abstract. We present deep high dynamic range infrared images of young nearby stars in the Tucana/Horologium and β Pic associations, all $\sim$ 10 to 35 Myrs young and at $\sim$ 10 to 60 pc distance. Such young nearby stars are well-suited for direct imaging searches for brown dwarf and even planetary companions, because young sub-stellar objects are still self-luminous due to contraction and accretion. We performed our observations at the ESO 3.5m NTT with the normal infrared imaging detector SofI and the MPE speckle camera Sharp-I. Three arc sec north of GSC 8047-0232 in Horologium a promising brown dwarf companion candidate is detected, which needs to be confirmed by proper motion and/or spectroscopy. Several other faint companion candidates are already rejected by second epoch imaging. Among 21 stars observed in Tucana/Horologium, there are not more than one to five brown dwarf companions outside of 75 AU ($1.5''$ at 50 pc); most certainly only $\leq 5\%$ of the Tuc/HorA stars have brown dwarf companions (13 to 78 Jupiter masses) outside of 75 AU. For the first time, we can report an upper limit for the frequency of massive planets ($\sim 10\ M_{jup}$) at wide separations (~ 100 AU) using a meaningfull and homogeneous sample: Of 11 stars observed sufficiently deep in β Pic (12 Myrs), not more than one has a massive planet outside of ~ 100 AU, i.e. massive planets at large separations are rare (≤ 9 %).

Key words: star formation – brown dwarfs – massive planets

1. Introduction: The target associations

Extra-solar planets have not been detected directly, yet. Direct imaging detection is difficult, because of the problem of dynamic range: Planets are too faint and too close to their much brighter primary star. However, young planets are still contracting significantly, so that the fraction of self-luminosity compared to luminosity due to reflected light is much higher in young planets than in old planets; therefore, young planets are much brighter than old ones (e.g. Wuchterl & Tscharnuter 2003). Hence, young nearby stars should be promising targets for direct imaging searches for sub-stellar companions, both brown dwarfs and giant planets.

A few brown dwarfs in orbit around young stars were confirmed so far by both proper motion and spectroscopy, e.g. TWA-5 (Lowrance et al. 1999, Neuhäuser et al. 2000b) and HR 7329 (Lowrance et al. 2000, Guenther et al. 2001), as well as two brown dwarf companions to the intermediate-age star HD 130948 (Potter et al. 2002, Goto et al. 2002), which is 200 to 800 Myrs old, possibly a member of the UMa group (see Potter et al. 2002).

Whether there is a *brown dwarf desert*, i.e. few brown dwarf companions, at large separations like it is found at small separations with radial velocity variations, can be in-

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vestigated best around young stars with a few tens of Myrs of age, because their brown dwarf companions have already formed and are still bright.

In recent years, nearby associations within 100 pc were found, each of which with a number of young stars, which are the targets of our campaign: The Horologium association (Torres et al. 2000; henceforth Tor00), the Tucana accociation (Zuckerman & Webb 2000, ZW00), and the β Pic group (Zuckerman et al. 2001b, Z01). The young stars in Tucana and Horologium are located next to each other on the sky, have distances from 45 to 60 pc, and an age around 35 Myrs, i.e. are possibly just one single association (Zuckerman et al. 2001a), which we call here Tuc/HorA. The β Pic moving group, though, may well be significantly younger, namely only ~ 12 Myrs (Z01).

Very low-mass companions around any of those member stars can improve age estimates of the primary star and, hence, the whole association, namely by using pre-main sequence tracks, because very low-mass stars at this age range (tens of Myrs) and all sub-stellar companions are above the main sequence, while most primary stars are already on or very close to the main sequence, so that age determination is difficult.

From all possible members of Tuc/HorA listed in table 1a in Tor00, we selected for our observations the F-type stars with a Lithium equivalent width W_{λ}(Li)$\geq$ 100 mÅ, the G-type stars with W_{λ}(Li)$\geq$ 200 mÅ, the K-type stars with W_{λ}(Li)$\geq$ 300 mÅ, and the M-type stars with W_{λ}(Li)$\geq$ 100 mÅ (see Neuhäuser 1997 for a discussion of the Lithium content per spectral type to be expected for pre-main sequence stars). Of those ten targets, we observed those six stars listed in Table 1.

In the Tuc part of Tuc/HorA, we selected the most likely members from table 1A in ZW00 which are listed as certain or possible nuclear members, adding others (from table 1A in ZW00) if they show either enough Lithium (criteria as above for Horologium stars) or if they show IR excess emission (HD 181296 and HD 207129), but excluding three members (PZ Tel, HR 7329, and HD 181327), which are instead included in the β Pic sub-sample. We added HD 202947 to our sample, a K-type stars with weak Lithium, because it is listed as eclipsing binary (of β Lyr type) in Simbad and Hipparcos, which would be of particular interest for the determination of its stellar parameters. See our Table 1 for our full Tucana sample, 15 of 16 likely members were observed by us with SofI and Sharp, namely all but HD 202917.

For a complete listing of β Pic moving group members, see Z01. Three of those members (PZ Tel, HR 7329, and HD 181327) were previously listed as probable or possible members of Tuc/HorA (in table 1A of ZW00). Two other members are HD 199143 and HD 358623, presented as Capricornius association of young nearby stars first by van den Ancker et al. (2000). Of a total of 19 member systems listed in Z01, we observed twelve, see Table 1 for the sub-sample observed by us.

In Table 1, we list all the stars observed by us with their V-band magnitude, spectral type, parallaxe, and information about multiplicity (from Simbad).

In section 2, we present the observations and data reduction and also list the resulting data. Then, in section 3, we discuss detected companion candidates, and in section 4, we investigate the dynamic range achieved and discuss the relevance of non-detections on the frequency of sub-stellar companions.

2. Observation and data reduction

We used two different IR imaging cameras, both at the 3.5m New Technology Telescope (NTT) of the European Southern Observatory (ESO) on La Silla, Chile: The MPE speckle camera SHARP-I (System for High Angular Resolution Pictures, Hofmann et al. 1992) with 256×256 pixel (scale 49.1 mas, determined from observing the Galactic Center in the same nights, and confirmed by the two wide stellar binaries AT Mic A & B and SAO 232842 & SAO 232841) and the normal 1k $\times$ 1k IR imager Son of Isaac (SofI[1]) used in the *small SofI field* mode with a pixel scale of 144 mas, the nominal pixel scale, confirmed by several wide stellar binaries with known separations as measured by Hipparcos; both pixel scales are measured with a precision of a few per cent. We observed during seven campaigns listed in Table 2.

The FWHM in the final Sharp-I images ranges from $0.21''$ to $0.78''$ with the mean being $0.45''$; and in the SofI images from $0.73''$ to $1.53''$ with the mean being $1.05''$ (see Table 3 for individual values).

In addition to the science targets, we also observed several photometric standard stars throughout each observing night (HR 8477, HR 7330, SAO 157131, HR 8278, HR 8658, and HR 6748). The nights 5/6 and 6/7 July 2001 were not photometric with some cirrus overhead, so that those data cannot be used for absolute photometry. Data reduction was performed in the normal way: We removed bad pixels, subtracted the medium dark from all frames, then devided all science frames by a medium flat field, and then subtracted the sky. Finally, we shifted and added the individual images up to a final image. In Table 3, we list all individual observations with instrument used, observing date, exposure time (on-source integration time without sky or overheads), full-width at half-maximum (FWHM), filter used, the observed (and previously known) magnitude of the primary, as well as detection limits for undetected companions achieved in the observation (in terms of detectable magnitude differences at different angular and projected physical separations).

All detected companion candidates within (somewhat arbitrarily) 500 AU are listed in Tables 4 & 5 with separations, position angles, and magnitudes; newly detected companion candidates, which are not yet rejected from a 2nd epoch image, are shown in Fig. 1 (Sharp) and 2 (SofI).

3. Results: Detected companions and candidates

Let us first discuss the detected companions candidates (Table 5), resolved known co-moving multiples (Table 4, top

[1] see www.ls.eso.org/lasilla/Telescopes/NEWNTT/

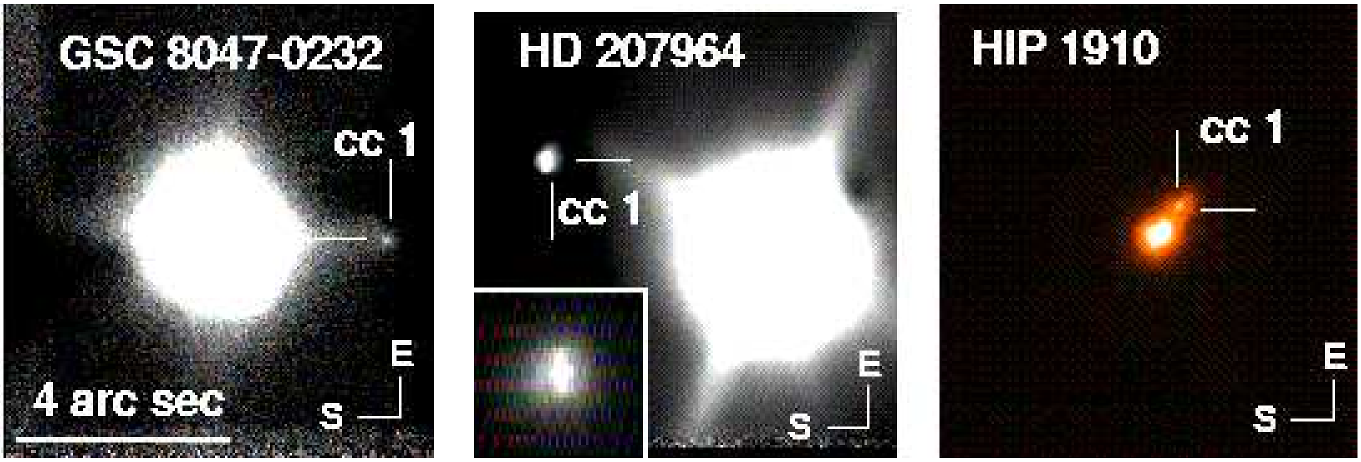

Fig. 1. Our Sharp K-band images of GSC 8047-0232 (left), HD 207964 (middle), and HIP 1910 (right), where we have detected new companion candidates; east up and south left, always $8'' \times 8''$. HD 207964 is a known sub-arc sec binary (WDS) somewhat elongated in our image (inlay in the central image, $1.7''$ aside), the PSF of the companion candidate is consistent with being single.

rows), and then, in the next section, detection limits and the relevance of non-detections. All companion candidates found around DS Tuc, PZ Tel, HD 139084, and AU Mic (listed in Table 4, bottom rows) were found to be non-moving background objects by our own 2nd epoch observations.

GSC 8047-0232: The faint companion candidate cc 1 three arc sec north of GSC 8047-0232 is the most promising in our data. At $\sim$ 45 pc distance, its absolute magnitude (M$_V$ = 11.1 ± 0.3 mag) is consistent with a 25 to 30 Jupiter mass object (for 100 Myrs) according to Chabier et al. (2000), or less massive for a younger age; at this absolute magnitude and age, it would be an early- to mid-L dwarf (e.g. Leggett et al. 2002). With B.C.$_K$ = 3.3 mag for early- to mid-L (Leggett et al. 2002), its bolometric luminosity (at 60 pc) would be $\log L_{bol}/L_{\odot} = -3.87 \pm 0.15$, corresponding to a mass of ~ 25 Jupiters (at 35 Myrs) according to Burrows et al. (1997). This companion candidate was detected independantly by Chauvin et al. (2003) by coronographic JHK-band imaging with ADONIS at the ESO 3.6m on La Silla, having $J, H, K \simeq 16.2, 15.2, 14.9$ mag, i.e. consistent with our value K= 15.0 ± 0.3 mag. This red color is indicative of an L-type brown dwarf companion. Follow-up spectroscopy can show whether it is a true companion or a reddened background star.

PPM 366328: The faint coompanion candidates near PPM 366328, all at $H \simeq 19$ mag, would be ~ 5 Jupiter mass objects (at 45 pc, 35 Myrs) according to Burrows et al. (1997) with B.C.$_K = 3.3$ mag, but at a projected physical separation of 400 to 500 AU, which is larger than expected for planets, so that they are probably background objects, like many of those in Table 4. A 2nd epoch follow-up image can show whether any of the companion candidates is co-moving with the primary star.

HD 207964: The faint companion candidate near HD 207964 at $K = 11.2 \pm 0.2$ mag, would be a $\sim$ 40 Jupiter mass object (at 46.5 pc, 35 Myrs) according to Burrows et al. (1997) with B.C.$_K$ = 3.3 mag, i.e. possibly a brown dwarf companion.

HIP 1910: The sub-arc sec companion candidate to HIP 1910 (separation of 639 ± 13 mas at 2001.5 with $K = 9.1 \pm 0.1$ mag) was also detected by Chauvin et al. (2003) with $H \simeq 9.47$ and $K \simeq 9.44$ mag at a separation of ~ 710 mas. At the magnitude difference between the primary and the companion candidate ($\Delta K = 1.6 \pm 0.2$ mag), it would be an early- to mid-M type companion, if bound. Then, its H-K color should be $\simeq 0.3$ mag. Because Chauvin et al. (2003) did not give errors to their magnitudes and separations (nor their observing date), we cannot judge, yet, whether our results are consistent and whether their H-K color for HIP 1910/cc 1 is consistent with early- to mid-M, nor whether the separation has changed between our and their observation.

HD 2884 and HD 2885: HD 2884 (β^1 Tuc) is a close $2.4''$ binary (A and B) with large magnitude difference (9.1 mag) according to the WDS with A being a spectroscopic binary (Aa and Ab), so that HD 2884 forms an hierachical triple. The magnitude difference between A and B is larger than our sensitivity limit (in a different band, though). The separation between the primary of the former (HD 2884 A) and HD 2885 (also β^2 Tuc or HD 2884 C) is $27''$ with HD 2885 being a close binary itself (C and D) with about half an arc sec separation (1.2 mag difference in WDS); the binary C and D (also called I 260, see WDS) was resolved by speckle imaging by Horch et al. (2000, 2001); they give $\Delta V = 1.2$ and $\Delta R = 1.2$ mag and list the binary as HD 2884 probably meaning C and D (i.e. HD 2885). We have resolved this close binary, too (see Table 4). Althogether, these objects form a quintuple. I 260 C & D have a separation of 0.58 to $0.59''$ at 1999.8 (Horch et al. 2000) the small change in separation (60 mas) and position angle (4°) in a few years indicates that this pair is most certainly a common proper motion pair (5σ), given the large proper motion of HD 2885 being 87.95 ± 4.14 and -45.79 ± 3.88 mas/yr (in α and δ) according to Hipparcos (see Perryman et al. 1997).

CoD$-53°386$: This pair is RST 47 A & B as listed in WDS, namely with $0.9''$ separation at a position angle of $312°$ with $\Delta V = 0.1$ mag at epoch 1930 (Rossiter 1933).

Table 3. Dynamic range achieved and limits on non-detections

Star	Instr.	Obs. date	Expo.	FWHM	Band	Primary magnitude			Magnitude limit (1)		
		[UT]	[sec]	[mas]		(2)	other	ref.	$0.5''$	$1''$	100 AU
Tuc/HorA (ZW00/Tor00): $\sim$ 35 Myrs at $\sim$ 50 pc, 13 Jup mass object has 17 mag in H or K											
CPD$-64°120$	Sharp	04 Jul 01	1200×0.5	445	K	8.1	8.1	(3)	11.7	14.4	16.6
GSC 8047-0232	Sharp	04 Jul 01	1200×0.5	236	K	8.7	8.4	(4)	12.3	15.0	17.2
CoD$-53°386$	Sharp	04 Jul 01	1200×0.5	385	K	8.6	8.5	(4)	11.7	14.2	15.9
HD 13183	Sharp	04 Jul 01	1200×0.5	543	K	7.2	7.1	(3)	10.5	13.0	15.9
GSC 8056-0482	Sharp	06 Jul 01	2400×0.5	577	K	n/p	7.5	(4)	10.9	13.2	15.4
SAO 232842	Sharp	06 Jul 01	2400×0.5	511	K	n/p	6.5	(4)	10.0	12.6	15.2
HD 177171	Sharp	07 Jul 01	2000×0.3	648	K	n/p	3.9	(3)	6.9	8.9	11.3
HD 202947	Sharp	04 Jul 01	1200×0.5	580	K	6.8	6.6	(4)	9.8	11.6	15.9
HD 202947	SofI	09 Dec 01	500×1.2	864	H	sat	7.0	(3)	sat	11.6	13.8
HD 207129	Sharp	05 Jul 01	1200×0.5	482	K	4.3	4.2	(3)	7.9	10.5	off
HD 207575	Sharp	05 Jul 01	1200×0.5	447	K	6.0	6.2	(4)	9.9	12.8	15.6
HD 207964	Sharp	05 Jul 01	1200×0.5	292	K	5.2	5.1	(3)	8.4	11.1	15.1
PPM 366328	SofI	20 May 00	460×1.3	1014	H	7.8	7.7	(3)	10.5	11.8	15.5
PPM 366328	SofI	09 Dec 01	500×1.2	795	H	7.8	7.7	(3)	9.5	11.2	15.0
HD 224392	Sharp	05 Jul 01	1200×0.5	490	K	4.9	5.1	(3)	8.8	11.6	13.2
DS Tuc	SofI	20 May 00	460×1.3	1170	H	sat	6.4	(3)	sat	9.9	13.8
DS Tuc	SofI	09 Jul 01	400×1.3	1099	H	sat	6.4	(3)	sat	11.0	13.3
HD 1466	Sharp	05 Jul 01	1200×0.5	435	K	6.0	6.1	(3)	9.9	12.8	15.9
HIP 1910	Sharp	05 Jul 01	1200×0.5	230	K	7.4	7.5	(4)	11.8	13.8	17.1
HIP 1993	Sharp	05 Jul 01	1200×0.5	352	K	7.6	8.3	(3)	12.3	15.3	18.3
HD 2884	Sharp	05 Jul 01	2000×0.2	356	K	4.4	4.5	(3)	8.4	11.2	13.9
HD 2885	Sharp	05 Jul 01	2890×0.2	209	K	4.7	4.7	(3)	8.7	11.6	13.9
HD 3003	Sharp	05 Jul 01	3000×0.2	389	K	5.0	5.0	(3)	9.0	11.6	14.3
HD 3221	Sharp	04 Jul 01	1200×0.5	446	K	6.8	6.6	(4)	10.4	13.3	16.5
β Pic (Z01): $\sim$ 12 Myrs at $\sim$ 40 pc, 13 Jup mass object has 15 mag in H or K											
HIP 23309	SofI	08 Dec 01	500×1.2	759	H	sat	7.1	(3)	11.6	12.9	16.7
HD 35850	SofI	09 Dec 00	400×1.5	896	H	sat	5.0	(3)	sat	13.4	18.4
AO Men	SofI	07 Dec 01	500×1.2	727	H	sat	7.0	(5)	12.6	14.1	15.9
HD 139084	SofI	18 May 00	460×1.3	1287	H	6.2	6.2	(3)	8.0	8.1	10.8
HD 139084	SofI	09 Jul 01	400×1.3	1353	H	sat	6.2	(3)	8.7	9.2	11.3
HD 139084	Sharp	07 Jul 01	1200×0.5	783	K	n/p	6.1	(3)	11.9	14.8	18.2
HD 155555	Sharp	06 Jul 01	1200×0.5	426	K	n/p	5.3	(3)	9.2	12.2	17.1
PZ Tel	SofI	18 May 00	460×1.3	1196	H	sat	6.5	(3)	sat	9.8	12.0
PZ Tel	SofI	09 Jul 01	400×1.3	994	H	sat	6.5	(3)	sat	12.9	15.9
HR 7329	see Lowrance et al. (2000), Guenther et al. (2001)										
HD 181327	SofI	18 May 00	460×1.3	1085	H	sat	6.0	(6)	sat	11.9	14.4
HD 181327	Sharp	06 Jul 01	2400×0.5	644	K	n/p	5.9	(6)	9.0	11.1	14.1
AT Mic	Sharp	02 Jul 01	1200×0.5	534	K	4.9	4.9	(5)	8.2	10.5	off
AU Mic	SofI	20 May 00	460×1.3	894	H	sat	5.1	(3)	sat	10.1	19.4
AU Mic	SofI	07 Dec 01	500×1.2	1534	H	sat	5.1	(3)	sat	8.9	16.9
HD 199143	see Jayawardhana & Brandeker (2001), Chauvin et al. (2002), Neuhäuser et al. (2002)										
HD 358623	see Jayawardhana & Brandeker (2001), Chauvin et al. (2002), Neuhäuser et al. (2002)										

Remarks: (1) Magnitude limit for undetected but detectable point-like objects measured as 3σ the flux in the bright star's PSF wing at that separation, converted to AU either with the known Hipparcos distance (Table 1) or the association's mean distance; *sat* for saturated on our SofI image; *off* means that this separation lies outside of the Sharp field-of-view. (2) This work, typically ± 0.1 mag, *n/p* for non-photometric conditions. (3) Estimated from V-band magnitude and spectral type as listed in Table 1 (from Simbad) using the colors given in Kenyon & Hartmann (1995), $\pm$ a few tenth of mag, because of errors in V, spectral type, color, and possible (unknown) IR excess. (4) From DENIS (L. Cambrésy, priv. com.), $\pm$ a few tenth of mag near the DENIS saturation limit (~ 8 mag), otherwise ± 0.1 mag. (5) From 2MASS, $\pm$ a few tenth of mag near the 2MASS saturation limit (~ 5 mag), otherwise ± 0.1 mag. (6) Sylvester & Mannings 2000.

The small change in separation in 71 years shows that the visual pair is a common proper motion pair, i.e. most certainly bound, given the proper motion of the primary being 38.2 ± 3.5 and -23.0 ± 3.3 mas/yr (in α and δ) according to Hipparcos (see Perryman et al. 1997).

4. Discussion: Detection limits and brown dwarf companion frequency

Let us now investigate the sensitivity limits determined for the dynamic range achieved in the images: The flux ratio is determined in all SofI and Sharp-I images as the 3σ background noise level on 7×7 pixel boxes as approximate PSF areas and devided by the peak intensity. We compare the ob-

Table 4. Companions and companion candidates detected twice

Secondary (1)	$\Delta\alpha$ (2) [mas]	$\Delta\delta$ (2) [mas]	Proj. sep. [AU] (2)	PA (3) [deg]	Comp. H [mag]	Date ddmmyy	Remarks
Known wide companions (common proper-motion pairs):							
PPM 366328 B	22980 ± 2 E	9187 ± 18 S	1113.7 ± 0.8	248.21 ± 0.05	9.6 ± 0.1	20 05 00	(4)
	22978 ± 2 E	9174 ± 5 S	1113.4 ± 0.3	248.24 ± 0.01	9.5 ± 0.1	09 12 01	(4)
DS Tuc B	1131 ± 11 W	5191 ± 31 N	246.0 ± 1.5	347.52 ± 0.21	saturated	20 05 00	(4)
	1131 ± 11 W	5191 ± 28 N	246.0 ± 1.4	347.52 ± 0.20	saturated	09 07 01	(4)
Rejected companion candidates (based on proper motions):							
DS Tuc A/cc 1	3511 ± 17 W	8624 ± 16 S	431.1 ± 1.6	202.15 ± 0.15	16.3 ± 0.3	20 05 00	(5)
	3589 ± 20 W	8514 ± 17 S	427.8 ± 1.8	202.86 ± 0.18	(n/p)	09 07 01	(5,6)
PZ Tel/cc 1	3168 ± 53 W	6768 ± 53 N	371.8 ± 5.3	334.37 ± 0.62	15.9 ± 0.3	18 05 00	
	3168 ± 54 W	6912 ± 53 N	391.4 ± 5.3	335.38 ± 0.62	(n/p)	09 07 01	(7)
HD 139084/cc 1	5760 ± 300 E	1368 ± 300 N	245 ± 15	163.0 ± 3.8	15.1 ± 0.4	18 05 00	
	6192 ± 300 E	1440 ± 300 N	263 ± 15	166.9 ± 3.6	(n/p)	09 07 01	(8)
HD 139084/cc 2	6927 ± 12 W	2788 ± 21 N	308.6 ± 1.5	291.92 ± 0.21	15.0 ± 0.3	18 05 00	
	6810 ± 18 W	2966 ± 30 N	306.9 ± 1.8	293.54 ± 0.31	(n/p)	09 07 01	(8)
HD 139084/cc 3	8219 ± 27 W	4495 ± 47 S	386.2 ± 2.5	241.57 ± 0.38	15.1 ± 0.3	18 05 00	
	8366 ± 18 W	4477 ± 30 S	392.1 ± 1.8	248.02 ± 0.25	(n/p)	09 07 01	(8)
HD 139084/cc 4	6193 ± 11 W	8267 ± 15 N	426.9 ± 1.4	323.16 ± 0.11	9.7 ± 0.2	18 05 00	
	6193 ± 11 W	8322 ± 15 N	428.7 ± 1.3	323.34 ± 0.11	(n/p)	09 07 01	(8)
HD 139084/cc 5	3610 ± 12 E	9956 ± 16 S	437.6 ± 1.4	160.07 ± 0.10	11.9 ± 0.2	18 05 00	
	3610 ± 11 E	9819 ± 14 S	432.3 ± 1.3	159.81 ± 0.11	(n/p)	09 07 01	(8)
AU Mic/cc 1	17136 ± 52 W	12528 ± 52 S	211.64 ± 1.58	233.83 ± 0.57	14.0 ± 0.2	20 05 00	
	17828 ± 34 W	11810 ± 31 S	212.57 ± 1.47	236.48 ± 0.14	14.1 ± 0.2	07 12 01	(9)
AU Mic/cc 2	25488 ± 53 E	3312 ± 53 S	256.25 ± 1.59	97.40 ± 0.58	14.7 ± 0.2	20 05 00	
	25054 ± 29 E	2616 ± 51 S	250.40 ± 1.52	95.96 ± 0.14	15.0 ± 0.2	07 12 01	(9)
AU Mic/cc 3	16704 ± 53 E	25056 ± 53 N	300.23 ± 1.59	33.55 ± 0.58	14.3 ± 0.2	20 05 00	
	16139 ± 26 E	25756 ± 41 N	302.14 ± 1.48	32.07 ± 0.58	14.5 ± 0.2	07 12 01	(9)
AU Mic/cc 4	12960 ± 53 E	34488 ± 53 N	366.23 ± 1.58	20.60 ± 0.58	13.2 ± 0.2	20 05 00	
	12292 ± 26 E	35088 ± 38 N	369.57 ± 1.47	19.31 ± 0.58	13.3 ± 0.2	07 12 01	(9)
AU Mic/cc 5	14544 ± 53 W	38736 ± 52 N	411.30 ± 1.58	339.42 ± 0.58	13.8 ± 0.2	20 05 00	
	15107 ± 25 W	39413 ± 32 N	419.58 ± 1.46	339.03 ± 0.58	13.9 ± 0.2	07 12 01	(9)
AU Mic/cc 6	26352 ± 53 W	41256 ± 52 N	486.62 ± 1.58	327.43 ± 0.58	13.5 ± 0.2	20 05 00	
	26930 ± 21 W	41920 ± 30 N	495.28 ± 1.45	327.28 ± 0.45	13.7 ± 0.2	07 12 01	(9)

Remarks: (1) Companion candidates with already confirmed common proper motion (i.e. most certainly bound companions) are designated *B*, other companion candidates are called *cc*. We list only those objects detected within (somewhat arbitrarily) 500 AU around the primary target. Those given with H-band magnitude are detected with SofI, those with K-band magnitude with Sharp. (2) Separation errors for α and δ include 10% error in pixel scale; error for total separation (in AU) includes 15% error for pixel scale and orientation together plus the error in distance. (3) Errors in position angles PA include 15% error for pixel scale and orientation together; PA is given as usual from North over East towards South. (4) This is a previously known wide binary (WDS) confirmed here: The separation has not changed or, putting it another way, the separation between the pair has changed within the errors by much less than the known proper motion of the primary star. (5) Separation and PA measured from the primary of the DS Tuc binary, i.e. the southern component. (6,7,8,9) Background object because of significant change in separation (α or δ or both) and/or PA, namely according to the known proper motion of the primary, but inconsistent with possible orbital motion. From the offset changes between star and companion candidate(s), now found to be non-moving background object(s), we obtain the proper motion given in remarks (6,7,8,9), always the correct direction and the correct order-of-magnitude (as in Hipparcos, see Perryman et al. 1997) after only about one year epoch difference. (6) We obtain $(\mu_\alpha, \mu_\delta) = (65 \pm 26, -92 \pm 23)$ mas/yr as proper motion, compared to Hipparcos: $(79.0 \pm 1.3, -67.1 \pm 1.1)$ mas/yr. (7) We obtain $(\mu_\alpha, \mu_\delta) = (0 \pm 75, -120 \pm 75)$ mas/yr as proper motion, compared to Hipparcos: $(16.6 \pm 1.3, -83.58 \pm 0.87)$ mas/yr. (8) We obtain $(\mu_\alpha, \mu_\delta) = (-44 \pm 29, -77 \pm 41)$ mas/yr as proper motion, compared to Hipparcos: $(-52.9 \pm 1.2, -105.99 \pm 0.98)$ mas/yr. (9) We obtain $(\mu_\alpha, \mu_\delta) = (365 \pm 174, -422 \pm 129)$ mas/yr as proper motion, compared to Hipparcos: $(280.4 \pm 1.7, -360.09 \pm 0.79)$ mas/yr.

served dynamic ranges with expected flux ratios for possible companions of different masses (calculated following Burrows et al. 1997) next to a mean primary star (Fig. 3).

The MPE speckle camera Sharp-I clearly gives the best dynamic range. In the Sharp images, we should have detected all sub-stellar companions above ~ 13 M$_{jup}$, i.e. all brown dwarfs, outside of $\sim 1.0''$, i.e. 40 AU (for the 12 Myrs young β Pic members at 40 pc); and in the SofI images, outside of $\sim 4''$, any brown dwarf would have been detected.

From those numbers of non-detections, we can derive upper limits for the frequency of brown dwarfs and massive planets in wide orbits around young stars: For 12 Myrs young stars (the β Pic members observed), no massive planets of ~ 10M$_{jup}$ outside of 40 AU are detected in a sample of six stars observed with Sharp (listed in Table 3 including HD 199143 and HD 358623 published in Neuhäuser et al. 2002). In the β Pic group, we also detected 13 wide possibly sub-stellar companions (listed in Table 4) around PZ Tel, HD

Table 5. Companions and companion candidates detected once

Secondary (1)	$\Delta\alpha$ (2) [mas]	$\Delta\delta$ (2) [mas]	Proj. sep. [AU] (2)	PA (3) [deg]	Comp. mag. H or K (4)	Date ddmmyy	Remarks
GSC 8047/cc 1	133 ± 8 W	3235 ± 20 N	145.7 ± 4.4	357.65 ± 0.18	K=15.0 ± 0.3	04 07 01	(5)
CoD$-53°386$ B	861.1 ± 8.6 E	907.6 ± 7.1 S	75.1 ± 1.6	36.50 ± 0.59	K=8.5 ± 0.1	04 07 01	(6)
HD 207964/cc 1	1674 ± 12 E	4479 ± 11 S	222.5 ± 1.0	159.51 ± 0.21	K=11.2 ± 0.2	05 07 01	(7)
PPM 366328/cc 1	7992 ± 52 E	4392 ± 52 N	410.4 ± 4.0	60.21 ± 0.51	H=19.3 ± 0.4	09 12 01	(8)
PPM 366328/cc 2	6120 ± 52 E	8280 ± 52 S	463.3 ± 4.0	126.47 ± 0.51	H=18.8 ± 0.3	09 12 01	(8)
PPM 366328/cc 3	216 ± 52 W	10584 ± 52 N	476.4 ± 4.0	358.83 ± 0.51	H=19.0 ± 0.4	09 12 01	(8)
HIP 1910/cc 1	492 ± 7 E	407 ± 11 N	29.55 ± 2.3	50.4 ± 1.4	K=9.1 ± 0.2	05 07 01	(5)
HD 2885 B	519.7 ± 9.9 W	26.1 ± 7.6 N	27.4 ± 4.4	272.88 ± 0.98	K=5.4 ± 0.1	05 07 01	(9)

Remarks: (1) to (3) as in Table 4. (4) Companion magnitude given in H for SofI and in K for Sharp. (5) These companion candidates were also detected by Chauvin et al. (2003). (6) Also called RST 47 A & B (WDS), see Sect. 3. (7) HD 207964 is a sub-arc sec binary (WDS), elongated in our image (see Fig. 1) with an additional faint companion candidate (called here cc 1). (8) The faint companion candidates are undetected in May 2000 due to limiting dynamic range and sensitivity due to poor atmospheric conditions. (9) Also called I 260 C & D (WDS), a sub-arc sec binary widely separated from to the triple star HD 2884, see Sect. 3.

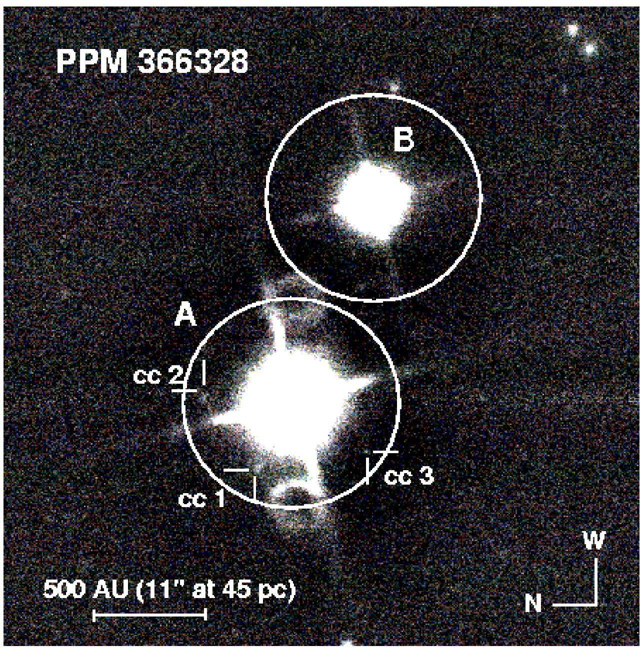

Fig. 2. Our SofI H-band image of PPM 366328 with the stellar binary A and B as well as three companion candidates within 500 AU around PPM 366328 A; north left, west up, $60'' \times 60''$. The circles have $10''$ radii, i.e. 500 AU at the assumed distance of Tuc/HorA (50 pc).

139084, and AU Mic, all of which were rejected by our 2nd epoch observations, i.e. all of them are unrelated background objects. Hence, there are no brown dwarf companion candidates left in the β Pic group outside of $1.0''$ (40 AU) in eleven stars observed either with Sharp or SofI.

As far as Tuc/HorA is concerned (35 Myrs at 50 pc), five possibly sub-stellar companion candidates are not yet rejected nor confirmed, namely three around PPM 366328 A with 400 to 500 AU projected separation, which are likely background stars, because they are very faint and widely separated, one around GSC 8047-0232, which is probably a brown dwarf companion (JHK color ok), and one around HD 207964, which may be sub-stellar (no color information). Hence, among 21 stars observed in Tuc/HorA, there are not more than one to five brown dwarf companions outside of 75 AU ($1.5''$ at 50 AU); most likely, just $\leq 5\%$ of the Tuc/HorA stars have brown dwarf companions (13 to 78 Jupiter masses) outside of 75 AU (GSC 8047). For more massive brown dwarf companions (35 to 78 Jupiter masses), we can set even stronger contraints on the separation: There is probably not more than one such brown dwarf among 21 stars observed detected outside of $0.5''$, i.e. 25 AU (HD 207964). Hence, the frequency of wide brown dwarf companions is small.

Around some of our targets, we could have detected massive planets at wide separations, see Table 3 for magnitudes expected for 13 Jup mass objects and magnitude limits achieved at a separation of 100 AU (last column). In Tuc/HorA, we can exclude planets with $\sim 10\ M_{jup}$ outside of ~ 100 AU only around GSC 8047, HIP 1910, and HIP 1993, too few stars for a statistical anaylsis. In the β Pic group, however, where such planets would be brighter (because younger), we can exclude them around ten stars: HIP 23309, HD 35850, AO Men, HD 139084, HD 155555, PZ Tel, and AU Mic (this work) as well as HR 7329, HD 199143, and HD 358623 (previous papers, see Table 3 for references). For one additional star, AT Mic, we did not probe separations outside 100 AU, because of its small distance and our limited Sharp field size[2]. We cannot include HD 181327 in this statistic, because our sensitivity at ~ 100 AU separation (14.1 mag, table 3) is not deep enough to detect $\sim 10\ M_{jup}$ mass objects (15 mag). Hence, among 11 stars probed at around ~ 100 AU separations, ten do not have wide massive planets, i.e. they are very rare ($\leq 9\ \%$).

Radial velocity surveys of nearby stars show that a significant fraction ($\geq 8\%$) have massive planets with orbital radii substantially less than that of Jupiter (Marcy & Butler 2000, Udry et al. 2000, Butler et al. 2001). Their close separation could be explained, e.g., by in-situ formation, inward migration, or by a close encounter with another (proto)planet, so that one planet has a very small, the other a very large separation. Hence, one might expect a similar number of massive

[2] AU Mic, though, forming a very wide common proper motion pair with AT Mic, i.e. located at roughly the same distance, is probed outside of 100 AU, because it was observed with SofI, i.e. with a larger field; AT Mic, however, is located outside the field on the AU Mic SofI images

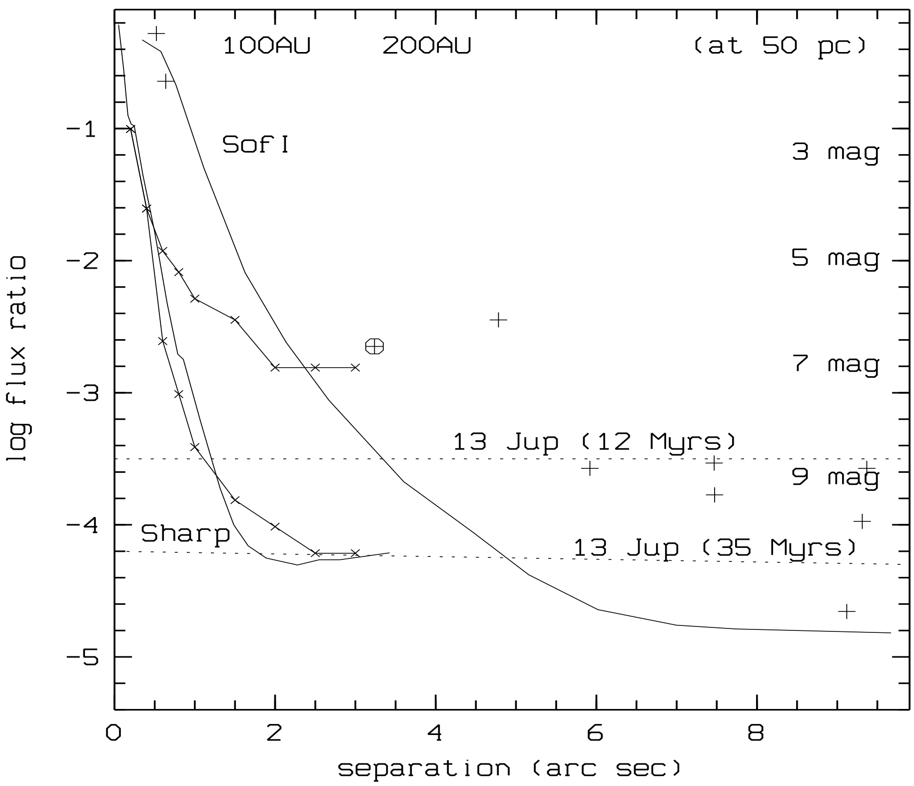

Fig. 3. Dynamic range achieved: Log of the flux ratio between primary and 3σ of the background limit versus separation for both a typical Sharp image (lower full line) and a typical SofI image (upper full line). We also indicate the expected flux ratios for 13 Jupiter mass companions at 12 (for β Pic) and 35 Myrs (for Tuc/HorA) as upper and lower broken lines, respectivelly, plotted as flux ratio compared to a primary with the mean H-band magnitude in our sample (6.3 mag). Also shown are the observed companion candidates as crosses with the most promising companion candidate GSC 8047/cc 1 circled. The two lines (with crosses inside) are the dynamic range achieved by Chauvin et al. (2003) with ADONIS (with Sharp-II) at the ESO La Silla 3.6m without coronograph (upper line) and with coronograph (lower line), taken from their figure 1. Comparing those lines to other Sharp result, they are quite identical within $0.5''$, and at wider separations, our Sharp dynamic range is comparable to the ADONIS dyanmic range when using the coronograph. Hence, as far as dynamic range is concerned, Sharp-I at the NTT is as good as ADONIS at the 3.6m with coronograph. The dynamic range achieved with the Sharp images shows that we would have detected all brown dwarf companions, i.e. all companions with mass above 13 Jupiters, at separations outside of $1.0''$ at 12 Myrs (i.e. in β Pic at 40 pc, i.e. outside 40 AU) and outside of $1.5''$ at 35 Myrs (i.e. in Tuc/HorA at 50 pc, i.e. outside 75 AU). In the Sharp images of β Pic stars, we could have detected massive planets ($\sim 10\ M_{jup}$) at 2 to $3''$ separations (80 to 120 AU at 40 pc). With SofI, 13 Jupiter mass companions are detectable only outside of $\sim 4''$ (200 AU at 50 pc).

planets in very wide orbits as in very close-in orbits. Also, if the frequency of massive planets is constant in log mass (Zucker & Mazeh 2002) and increasing in log period (Armitage et al. 2002), than one should again expect roughly as many massive planets in wide orbits as in close orbits. By direct imaging, one can currently detect only planets in wide orbits. Our upper limit for their frequency ($\leq 9\ \%$) is consistent with the frequency of known Pegasi planets (few $\%$). The non-detection of wide massive planets does not mean that encounters of protoplanets are rare (due to limited statistics). We note that none of the objects observed here is known to have a radial velocity planet candidate; young stars are difficult targets for radial velocity planet searches because of the intrinsic activity, hence radial velocity scatter.

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Table 1. Our sample

Star	V [mag]	Spectral type	Parallaxe π [mas]
Tuc/HorA (ZW00/Tor00): ~ 35 Myrs at ~ 50 pc			
CPD$-64°120$	10.2	K1	
GSC 8047-0232	10.9	K3	
CoD$-53°386$	11.0	K3	
HD 13183 (1)	8.7	G5	19.93 ± 0.79
GSC 8056-0482	12.1	M3	
SAO 232842 (2)	8.4	G7	
HD 177171 (3)	5.2	F7	19.07 ± 0.79
HD 202947 (4)	8.9	K0+K2.5	21.7 ± 1.5
HD 207129 (5)	5.6	G0	63.95 ± 0.78
HD 207575	7.2	F6	22.18 ± 0.80
HD 207964 (6)	5.9	F0+F1	21.49 ± 0.67
PPM 366328 (7)	9.6	K0	
HD 224392	5.0	A1	20.53 ± 0.51
DS Tuc	8.0	G6+G8	21.6 ± 1.3
HD 1466	7.5	F9	
HIP 1910	11.3	M1	21.6 ± 2.2
HIP 1993	11.5	K7	27 ± 24
HD 2884 (8)	4.3	B9	23.35 ± 0.52
HD 2885 (6,8)	4.5	A2+A7	19.0 ± 4.4
HD 3003	5.1	A0	21.52 ± 0.49
HD 3221	9.6	K4	21.8 ± 1.0
β Pic (Z01): ~ 12 Myrs at ~ 40 pc			
HIP 23309	10.1	K7	38.1 ± 1.1
HD 35850	6.3	F7	37.26 ± 0.84
AO Men	10.1	K3	26.0 ± 1.0
HD 139084	8.1	K0	24.2 ± 1.1
HD 155555	6.9	G5+K0+M4.5	31.83 ± 0.74
PZ Tel	8.4	K0	20.1 ± 1.2
HR 7329	5.0	A0+M8	20.98 ± 0.68
HD 181327	7.0	F5.5	19.77 ± 0.81
AT Mic (9)	10.3	M4+M5	97.8 ± 4.7
AU Mic (9)	8.6	M0	100.6 ± 1.4
HD 199143	7.3	F8+M2	21.0 ± 1.0
HD 358623	10.6	K7+M3	(10)

Remarks: (1) Single-lined spectroscopic binary (Cutispoto et al. (2002). (2) Secondary to SAO 232841 (8.7$''$ off), a double-lined binary (F8+K0) with weak Lithium (Tor00). (3) Double-lined spectroscopic binary (ZW00). (4) An eclipsing binary with a few day period according to the Hipparcos light curve solution and SB2 according to Cutispoto et al. (2002) with Li detected only in the primary, but Ca H & K emission in both components. (5) Visual companion 3 mag fainter in V separated by about one arc min (WDS). (6) Known sub-arc sec visual binary. (7) Wide binary with CPD$-64°4331$ B with $\Delta V = 5.2$ mag (WDS). (8) The binary HD 2885 and the triple HD 2884 form a quintuple. (9) The binary AT Mic and the apparently single star AU Mic form a very wide common proper motion pair (WDS). (10) HD 358623 has the same proper motion as HD 199143 and is located nearby, so that it most certainly has the same distance as HD 199143 (van den Ancker et al. 2000).

Table 2. Observing log

Instrument	Dates (local)	Program
NTT/SofI	17-19 May 2000	65.L-0144(B)
NTT/SofI	07-08 Dec 2000	66.D-0135(A)
NTT/SofI	04-07 Mar 2001	66.C-0310(A)
NTT/Sharp	01-06 Jul 2001	67.C-0213(A)
NTT/SofI	08 Jul 2001	67.C-0209(B)
NTT/SofI	06-07 Dec 2001	68.C-0009(A)
NTT/SofI	08 Dec 2001	68.C-0008(A)

fahrt e.V. We have made use of the Simbad database operated at the Observatoire Strassburg.

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